A MEASUREMENT OF THE PRIMARY PROTON FLUX FROM 10 TO 100 MeV

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NASA CR-53448; (EFINS-63-78)

A MEASUREMENT OF THE PRIMARY PROTON FLUX FROM 10 to 130 MeV*‡

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0591032

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Submitted ~~to~~ for Publication

Journal of Geophysical Research

Feb~~ruary~~ 1964 24p refs

* This research was supported in part by the Air Force Office of Scientific Research under contract AF 49 (638)-1008 and grant AF-AFOSR-62-23, and by the National Aeronautics and Space Administration under grant ~~NASA~~ NSG-179-61; (NASA Grant Grant); and Contract AF49(638)-1008

‡ A thesis submitted to the Department of Physics, the University of Chicago, Chicago, Illinois, in partial fulfillment of the requirements for the Ph.D. degree.

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ABSTRACT

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A counter telescope, composed of nine Au Si solid state detectors for measuring the energy loss and range of vertically incident particles, was carried into a polar orbit by an oriented satellite on 12 December 1961. The choice of detectors and absorbers allowed separation of protons and alphas with energies between 10 and 250 MeV/nucleon. Although the quantity of data was limited by the failure of the vehicle transmitter, both the observed 85 – 130 MeV proton flux and the alpha flux are consistent with other 1961 observations. In addition, a proton flux of $\sim 1\ m^{-2}\ sec^{-1}\ sr^{-1}\ MeV^{-1}$ was measured in the 10-85 MeV energy range, which indicates that the quiet time spectrum was much "flatter" than the E^{-2} spectrum that others observed at higher energies.

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INTRODUCTION

The energy spectrum of low energy extraterrestrial protons is important in the study of solar modulation of galactic cosmic rays and in the study of solar emission of energetic protons. The continuous presence of a small flux of 80-350 MeV protons at a time (1960) near maximum solar activity was first reported by Vogt(1962). In 1961, Bryant, Cline, Desai and McDonald (1962) observed a similar flux. Further studies in 1961 by Meyer and Vogt (1963) led to their suggestion that the 80 - 200 MeV flux was of solar origin, and either was released continuously or was ejected by a large flare and stored in interplanetary space for $\gtrsim$ 30 days.

The present satellite experiment was designed to investigate further the above modulation and production effects by determining the spectrum of vertically incident 10 - 130 MeV extraterrestrial protons. This choice of energy interval allowed both the comparison with the above spectra in the 80-130 MeV region and the measurement of 10 - 80 MeV protons which are absorbed in the air before reaching balloon-borne equipment.

The results of the experiment were severely limited by the failure of the satellite transmitter. However, the available proton data for 13 December 1961 are consistent with the above results in the 80 - 130 MeV interval, and indicate that solar emission of protons must have extended down to 10 MeV. The 10 - 80 MeV proton differential energy spectrum is relatively flat; the flux of $\sim 1\ m^{-2} sec^{-1} sr^{-1} MeV^{-1}$ is much less than that obtained by extrapolating the E^{-2} spectrum observed by others for 90 - 200 MeV protons. These results were presented in a preliminary report (Stone, 1963).

INSTRUMENTATION

By measuring the dE/dx and range of a particle, it is possible to identify both its charge and energy. The counter system used for this combination of measurements is shown in Figure 1. The detectors were surface barrier (AuSi) solid state diodes with characteristics similar to those listed in Table I. The energy loss of a particle incident from above as it traverses the depletion (sensitive) regions of detectors PH1A and PH1B is used as a dE/dx measurement. The range of the particle is indicated by the number of range detectors (R1 through R5 in Figure 1) penetrated by the particle. The lead absorbers increase the range intervals between successive detectors. The detector system was sealed in 1 atm of dry N_2.

The calculated average energy loss of protons and alphas in the combined depletion widths of PH1A and B as a function of incident energy is indicated in Figure 2. The calculation assumed a total depletion depth of 450 microns of silicon (see below for calibration). The calculated spread in proton energy losses is based on the measured noise level and a calculation of the statistical (Landau) fluctuation in energy loss (Rossi, 1952). Sixty-seven percent of the measurements should lie between the limits shown in Figure 2. The 6 MeV/nucleon threshold is due to an aluminized mylar light baffle and the non-depleted silicon of detector PH1A. Figure 2 also indicates the last range detector that a particle with a given energy will reach. Note that in no case do protons and alphas with the same dE/dx have the same range indication. The separation of protons and alphas is also possible without detector R4, which failed before flight and was not replaced. The 320 keV threshold was set electronically, and was as near as possible to the amplifier noise. With this threshold, all relativistic alphas are detected, but protons with > 250 MeV are not. However, the detection efficiency for protons with energy losses near threshold is dependent on statistical fluctuations, restricting proton flux measurements to energies less than 125 MeV.

The acceptance angle of the telescope was defined by detectors PH1 and R1. Because the largest detectors available in quantity at that time were ~ 2.5 cm^2 in area, the detectors R1 through R3 did not cover the entire acceptance cone of PH1 - R1. For the same reason, the R5 detector was a mosaic of 4 detectors. The necessary geometrical correction factors are indicated in Table II in the form of a coefficient ϵ_{ta}, where t is the true range, in terms of penetrating R1 through R5, and a is the observed range. For example $\epsilon_{31} = 0.12$ means that 0.12 of the events with a true range equivalent to R3 will indicate a range of R1 because they miss detectors R2 and R3. The only correction of significance is associated with $\epsilon_{53} = 0.12$, because relativistic alphas with true range equivalent to R5 have the same dE/dx as 80 MeV protons with true range equivalent to R3. The geometrical corrections are not important in the other intervals because the corresponding alpha flux is small.

The electronic circuitry associated with the counter telescope, although complicated in detail, can be summarized briefly:

1) Charge-sensitive amplifiers produced output voltage pulses proportional to the number of electron-hole pairs created in the silicon detector by an ionizing particle.

2) A 128-channel height-to-time converter (pulse height analyzer) recorded the combined responses of detectors PH1A and PH1B to the dE/dx of incident particles.

3) Appropriate logic circuits recorded the maximum range (R1 through R5) corresponding to each pulse height analyzed event.

4) Auxiliary coincidence counting rate scalers and single detector counting rate scalers operated independently of the dE/dx-range system and provided supplemental information on individual detector performance.

The pulse height and range of a given event are sampled once each second until a new event occurs. At low counting rates, this built-in redundancy increases the amount of noise-free data from telemetry.

CALIBRATION

The calculated energy loss shown in Figure 2 is based on a total effective depletion depth of 450 microns (= 109 mg-cm^{-2} silicon). This value was determined by calibrating the solid state detectors with energetic protons accelerated by the University of Chicago synchrocyclotron. Figure 3 is a plot of the measured energy loss in PH1A and B versus the theoretical dE/dx. The slope of the best fit line yields a combined depletion depth of 449 $\pm$ 17 microns (109 mg-cm^{-2}). This is in reasonable agreement with the single detector depletion depth predicted on the basis of the resistivity of the silicon and the applied bias voltage (Table 1).

CORRECTIONS FOR NUCLEAR INTERACTIONS

As high energy protons and neutrons penetrate the telescope, they will occasionally interact with the silicon and lead nuclei. The telescope response to the secondaries from these nuclear interactions has been calculated in detail, following a technique suggested by Vogt (1961) for the calculation of secondary production in the top layers of the atmosphere. This detailed calculation includes consideration of the spectra, multiplicity, and angular distribution of the secondary particles as determined by extensive balloon-borne emulsion studies (see Rossi, 1952, for a review). Emulsion studies from recovered Discoverer satellite capsules (Yagoda, 1962) provided information on the nuclear interaction rate. The results of this detailed calculation indicate that the only significant contribution of nuclear interactions occurs with a small energy loss and a Range 3 indication and therefore would be confused with 60 - 125 MeV primary protons. The calculated secondary rate is one-fourth of the observed rate in this interval. The correction is largest for this interval because of the large amount of lead between detectors R3 and R5. Since there is much less material between R1 and R2, and R2 and R3, the secondary contribution to these range intervals is much less. In addition, most of the secondaries will deposit less than four times minimum (< 720 keV) in PH1. Thus, the detailed calculation indicates that nuclear interactions make no significant contribution to the range-energy loss intervals corresponding to alphas and to protons with < 60 MeV.

FLIGHT

This experiment was launched 12 December 1961 on Discoverer 36 (see Table III for orbital characteristics).

During the time of the experiment, the vehicle was oriented so that the axis of the counter telescope was only 17° from the vertical. Unfortunately, the usefulness of the flight was severely restricted by noisy transmission in the first orbits and complete loss of transmission after orbit 9. However, the inflight tape recorded data from one orbit were received in excellent condition and are the basis for this report.

RESULTS

The analysis of all proton and alpha events recorded in the polar region ($> 65^{o}$) is listed in Table IV. As previously pointed out, the geometrical and secondary corrections are important only in the 60 - 125 MeV interval. The errors on the flux figures are 67% confidence levels for a Poisson distribution, corresponding roughly to the standard deviation quoted for normal distributions. The low single detector counting rates eliminate the possibility of accidental analysis.

The alpha fluxes are included in Table IV to permit comparison with other measurements. Fichtel and Guss (1963) find J(>100 MeV/nuc) = 205 ± 11 $m^{-2}sec^{-1}sr^{-1}$ and J(> 600) = 151 ± 11 $m^{-2}sec^{-1}sr^{-1}$ from balloon borne emulsions launched at Fort Churchill, Manitoba, on 8 July 1961. Both their measurement and the present one were preceded by at least 10 days of no solar flare activity. Thus, the reasonable agreement of the two measurements reinforces the validity of the data presented here.

In order to further demonstrate the consistency of the data, all of the proton events recorded in the equatorial regions ($<45^{o}$) are listed in Table V. As noted, the number of protons observed agrees well with the calculated return albedo (Ray, 1962), taking into consideration the orientation of the telescope and averaging over the values predicted for the different latitudes.

In addition to the events listed in Tables IV and V, about 50 events were recorded with energy losses less than 500 keV, corresponding to protons with > 125 MeV and to electrons with > 500 keV. However, the small signal-to-noise ratio for these events makes it difficult to account for the efficiency of their detection by the various range counters.

DISCUSSION

The solar activity preceding this observation was quite low. A recurrence phenomena was observed by Explorer XII (Bryant, Cline, Desai, and McDonald, 1963) on 1 December 1961. By 4 December 1961, all geophysical effects associated with this event were gone and during the following 10 days there were no solar radio events, a very low sunspot number, and only six small optical flares (Solar-Geophysical Data, Part B, CRPL). Thus the protons observed on 13 December 1961 represent a quiet-time flux.

The low energy spectrum reported here is plotted in Figure 4 as are the higher energy spectra reported for 1961 by Meyer and Vogt (1963), using a balloon-borne range-energy loss counter telescope (Vogt, 1962); by Bryant, Cline, Desai, and McDonald (1962), using a satellite-borne dE/dx counter telescope; and by Fichtel and Guss (1964), using balloon-borne emulsions. All of the data were obtained during times not immediately preceded by large solar flares. The counter experiments are all consistent, but in disagreement with the emulsion measurements.

The present results are in reasonable agreement with those of Meyer and Vogt (1963) and with those of Bryant, et. al. (1962) in the 60 - 130 MeV interval, suggesting that the lower energy flux is of the same nature as the 80-200 MeV flux. It is clear from Figure 4 that the low energy data is entirely inconsistent with an extension of the spectrum observed at higher energies. The 10-80 MeV flux could be best characterized as $\sim 1\ m^{-2}sec^{-1}sr^{-1}MeV^{-1}$, but it is also consistent with a constant differential rigidity flux as suggested by the data of Bryant, et. al. (1962). The statistical errors inherent in such a small number of events prevent a more specific spectral determination.

Comparing data recorded during different times in the solar cycle, Meyer and Vogt (1963) have concluded that the flux in the 80 -200 MeV interval is of solar origin, and that either it is produced or released constantly (not only by larger flare events), or that it is produced by large flare events and stored approximately thirty days in interplanetary space. The present observation at lower energies cannot resolve the two possibilities, but it does indicate that a similar mechanism could be operative down to 10 MeV, producing fluxes of the order of $1\ m^{-2}sec^{-1}sr^{-1}\ MeV^{-1}$.

ACKNOWLEDGMENTS

Special thanks are extended to my faculty sponsor, Dr. J. A. Simpson, for suggesting this problem and providing continued support.

This experiment was made possible by the design and fabrication of the satellite package by the staff of the Laboratory for Applied Sciences of the University of Chicago, which was under the guidance of J. E. Lamport. A. Tuzzolino and M. Perkins developed and directed the fabrication of the solid state detectors which were crucial to this experiment, and B. Arneson, R. Jacquet, R. Takaki, and R. Weissman designed the associated electronic circuitry. H. Thomas was responsible for the mechanical design, D. DiConstanzo supervised the mechanical fabrication, W. Six directed the quality control program, and J. Jezewsky supervised final packaging. R. Blenz, E. Drag, R. Draus, J. Stepney, H. Tibbs, W. Urry, and L. Work provided the technical competence necessary for the construction of reliable, flight-worthy electronics. In addition, W. Mankawich and A. Hoteko helped with special engineering problems, and L. Petraites assisted during pre-launch activities. Pre-flight checkout and post-flight analysis were greatly aided by the efforts of R. Glosser and M. Israel. Without the generous cooperation of all of the above individuals, the experiment would not have been possible.

The experiment was launched on Discoverer 36 under the auspices of the Geophysical Research Directorate, Air Force Cambridge, through the efforts of Dr. L. Katz and Mr. L. Letterman. Dr. F. Seward of Lawrence Radiation Laboratory (LRL) kindly provided the timing parameters necessary for reducing the tape recorded data. Channels on the flight tape recorder were available to us through the generosity of the LRL group.

The synchrocyclotron calibration was simplified by the prior calibration of the proton beam by Dr. R. Vogt at Chicago. The preliminary calibration was made through the generous aid of Dr. M. Kaplon and the synchrocyclotron group at the University of Rochester.

I am grateful to Drs. C. E. Fichtel and D. Guss for the communication of their results prior to publication.

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TABLE I

ESSENTIAL CHARACTERISTICS OF THE PROTON-ALPHA INSTRUMENT

Typical AuSi Surface Barrier Detector:	
Total Thickness	120 mg-cm^{-2} Si
Depletion Thickness	50 mg-cm^{-2} Si
Sensitive Area	2.5 cm^{2}
Electronic Discrimination Level (Single Detector)	160 keV
Geometrical Factor; PH1-R1 Coincidence	0.59 cm^{2} sr

TABLE II

GEOMETRICAL CORRECTION FACTORS

t = True Range

a = Apparent Range

		a			
t	Range	1	2	3	5
1	R1	1.0	-	-	-
2	R2	0.12	0.88	-	-
3	R3	0.12	0.15	0.73	-
5	R5	0.05	0.08	0.12	0.75

TABLE III*

DISCOVERER 36, 1961 αK 1

Launch	12 December 1961 at 2022 UT
Orbital Inclination	81.21°
Nodal Period	91.82 min
Perigee Height	241 km
Apogee Height	484 km

* Rees and King-Hele, 1963

TABLE IV

POLAR DATA (1518 SECONDS)

Particle	Energy MeV/Nuc	Number Observed	Nuclear Interaction Correction	Geometrical Correction	Flux
p	11-18	1	0	0	$1.6^{+3.7}_{-1.3}$ $m^{2}sec^{-1}sr^{-1}MeV^{-1}$
	18-27	2	0	0	$2.8^{+3.5}_{-1.8}$
	27-60	2	0	0	$0.9^{+1.1}_{-0.6}$
	60-125	7	-2	-1	$0.9^{+0.7}_{-0.4}$
α	>560	8	0	0	120^{+60}_{-40} $m^{2}sec^{-1}sr^{-1}$
	> 80	16	0	0	240^{+80}_{-60}

TABLE V

EQUATORIAL DATA (2000 SECONDS)

PROTONS

Energy (MeV)	Number Observed	Notes
11-27	0	
27-60	4	Predicted Albedo: 2.3
60-125	3	Predicted Albedo: 2.2 Geometrical Correction: 1 Total predicted 3.2

FIGURE CAPTIONS

Fig. 1. Cross section view (not to scale) of the arrangement of circular solid state detectors and lead absorbers in the dE/dx-range telescope. Detectors PH1A and PH1B measure the dE/dx of the particle. Detectors R1 through R5 indicate the range of the particle. Note that detectors R5 is a mosaic of four detectors, as shown in top view.

Fig. 2. The calculated average energy loss of protons and alphas in the combined depletion regions of PH1A and PH1B versus the incident energy/nucleon of the particle. The maximum range detector reached by the particles is also indicated. Sixty-seven percent of the protons will have energy losses within the limits shown for Landau and noise spread.

Fig. 3. Determination of the width of the combined depletion regions of PH1A and PH1B by comparing the measured energy loss to the theoretical dE/dx for protons.

Fig. 4 The 10 - 130 MeV proton differential energy spectrum. Other observations of the higher energy spectrum are also indicated. The dashed spectrum for $E >$ 350 MeV is from Meyer and Vogt.

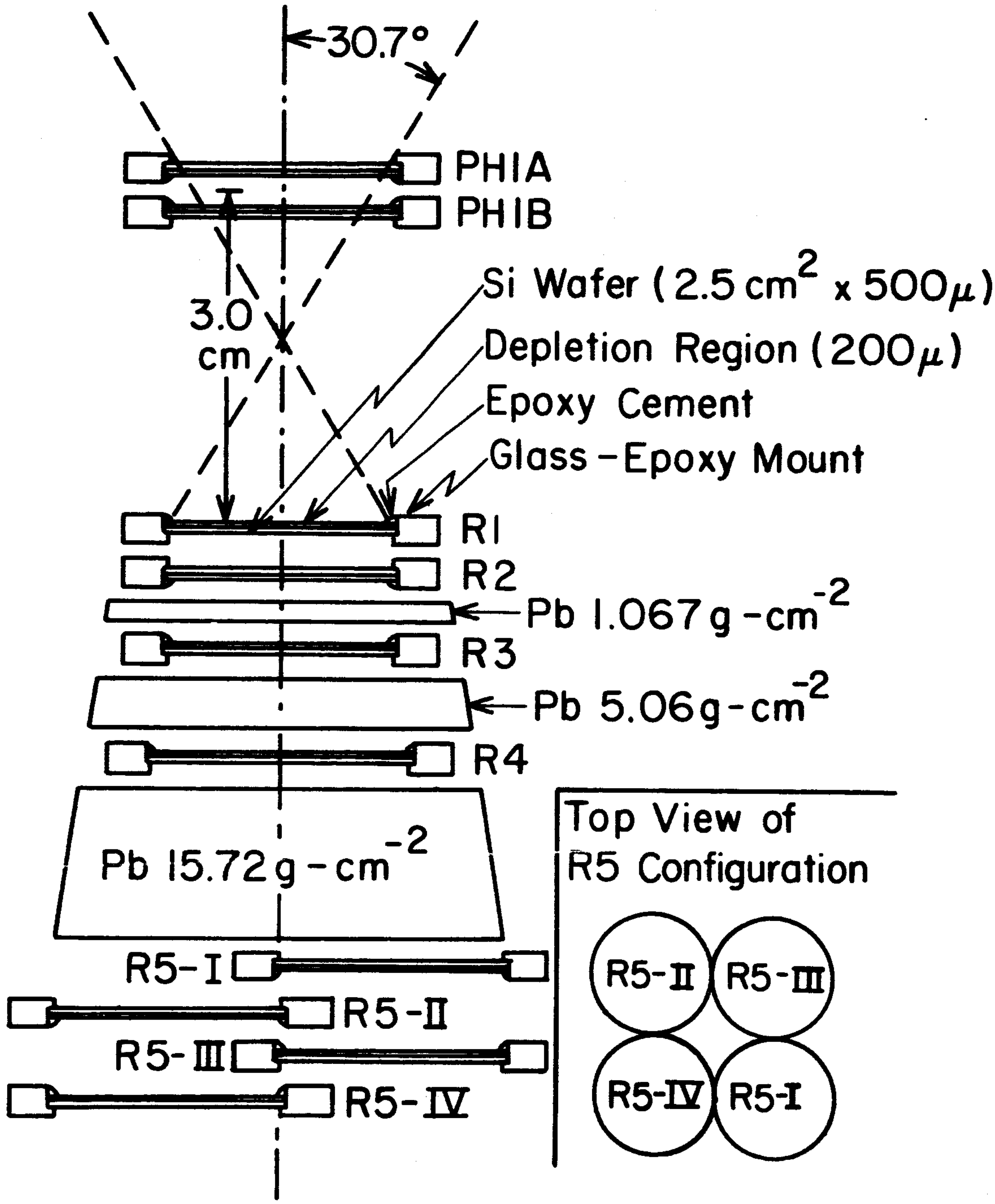

30.7°
PHIA
PHIB
3.0 cm
Si Wafer (2.5 cm^2 x 500μ)
Depletion Region (200μ)
Epoxy Cement
Glass-Epoxy Mount
R1
R2
Pb 1.067 g-cm^{-2}
R3
Pb 5.06 g-cm^{-2}
R4
Pb 15.72 g-cm^{-2}
R5-I
R5-II
R5-III
R5-IV
Top View of R5 Configuration
R5-II
R5-III
R5-IV
R5-I

Fig. 1

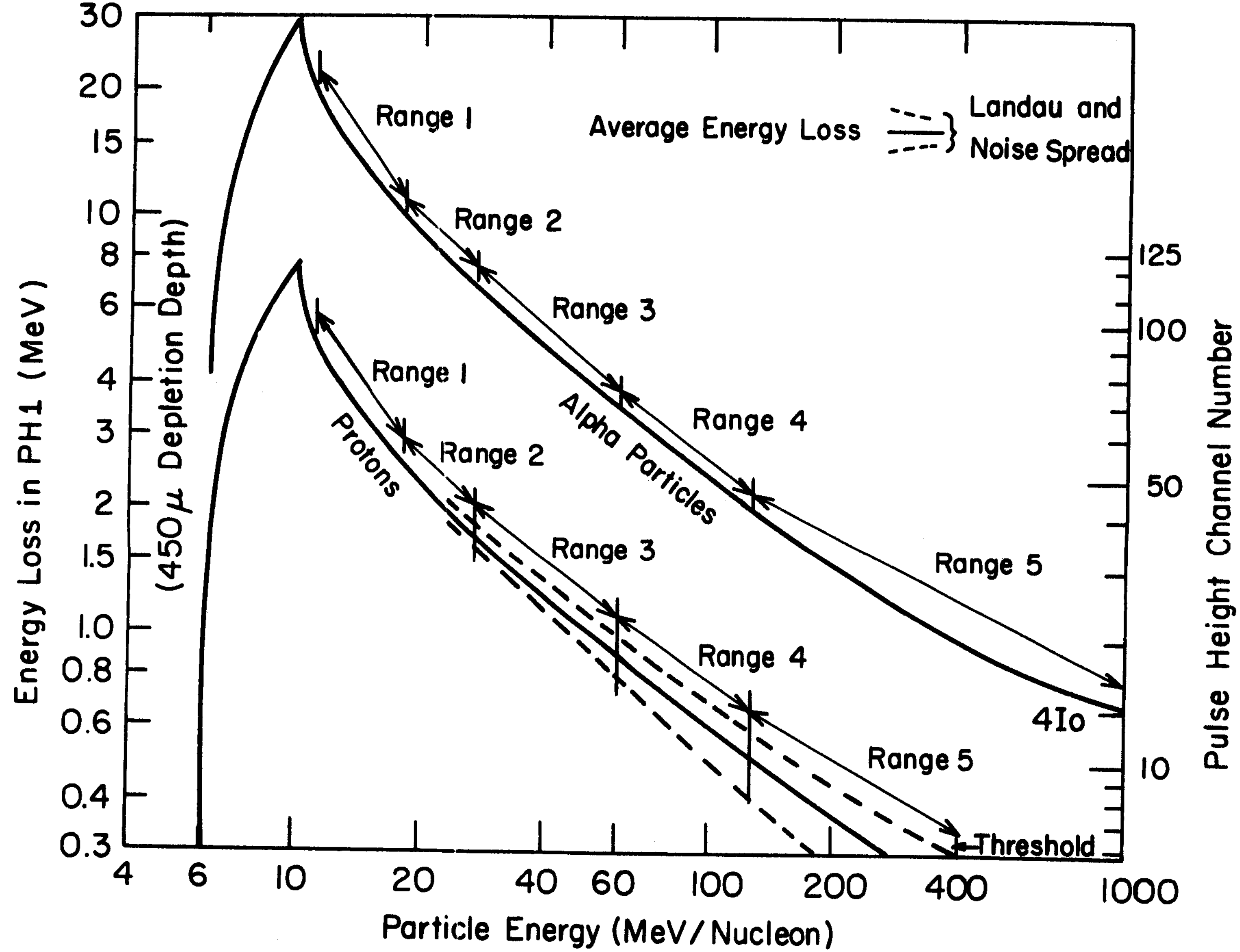
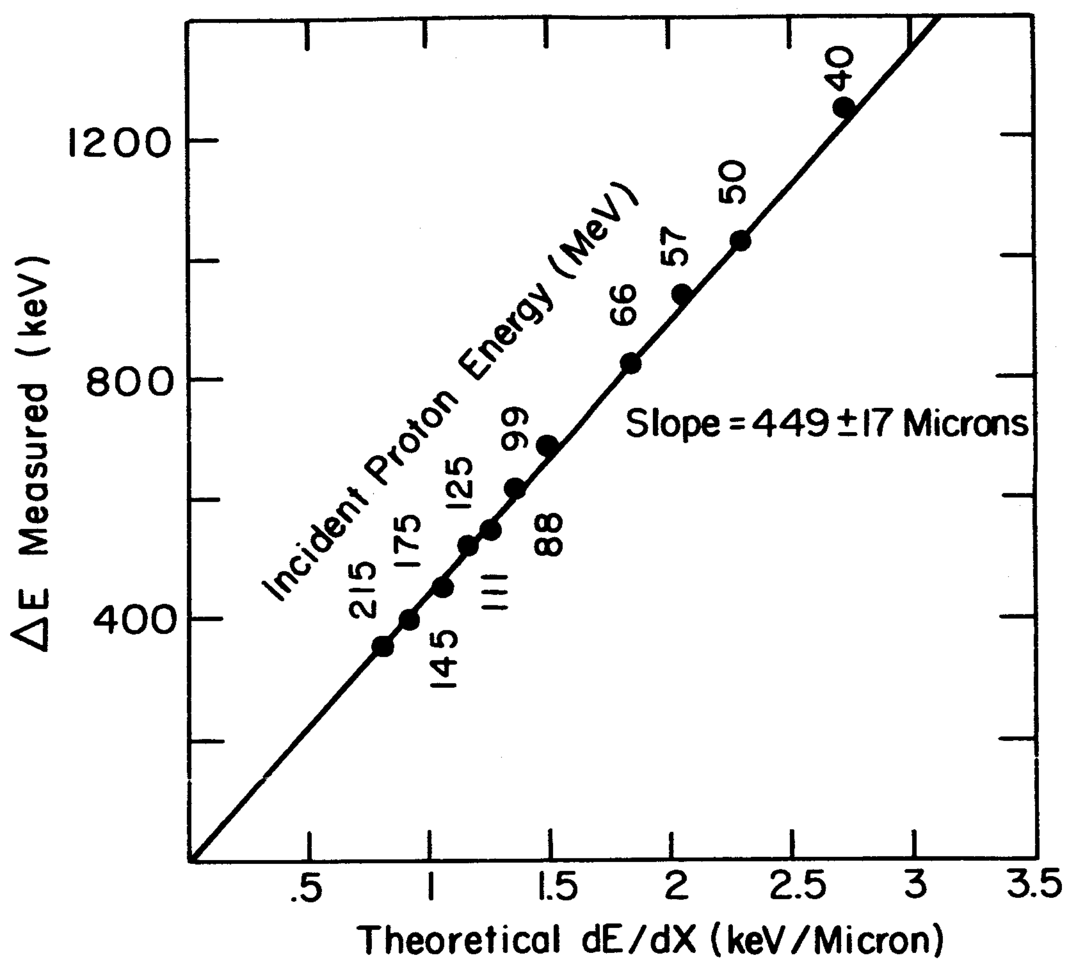
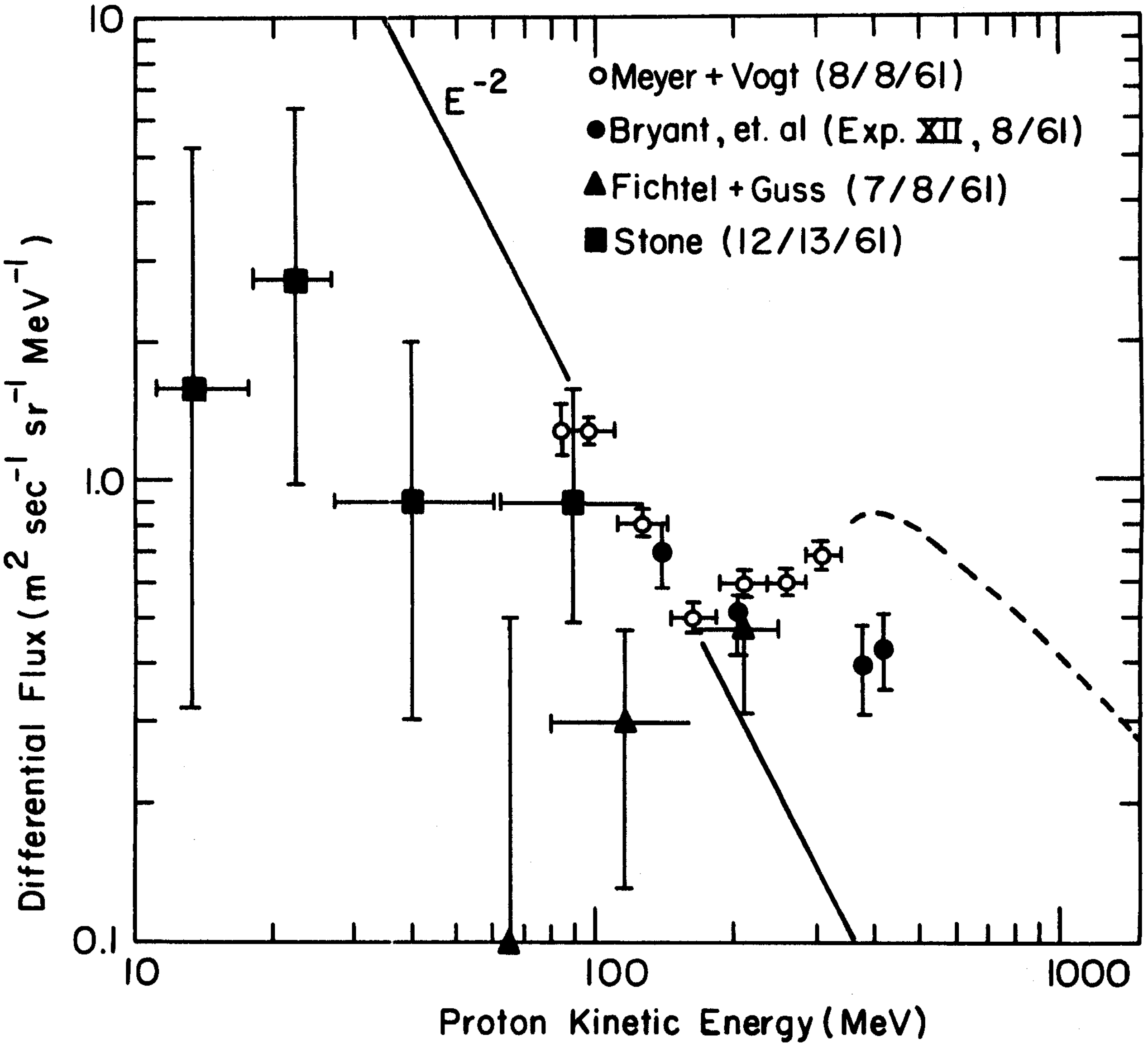

Energy Loss in PH1 (MeV)
(450μ Depletion Depth)
Pulse Height Channel Number
Particle Energy (MeV/Nucleon)
Average Energy Loss
Landau and Noise Spread
Range I
Range 2
Range 3
Range 4
Range 5
Alpha Particles
Protons
4Io
Threshold
30
20
15
10
8
6
4
3
2
1.5
1.0
0.8
0.6
0.4
0.3
4
6
10
20
40
60
100
200
400
1000
125
100
50
10

Fig. 2



1200
800
400
ΔE Measured (keV)
.5
1
1.5
2
2.5
3
3.5
Theoretical dE/dX (keV/Micron)
Incident Proton Energy (MeV)
215
175
145
125
111
99
88
66
57
50
40
Slope = 449 ± 17 Microns

Fig.3



10
1.0
0.1
10
100
1000
E^-2
○Meyer + Vogt (8/8/61)
●Bryant, et. al (Exp. XII, 8/61)
▲Fichtel + Guss (7/8/61)
■Stone (12/13/61)
Differential Flux (m^2 sec^-1 sr^-1 MeV^-1)
Proton Kinetic Energy (MeV)

Fig. 4